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This is the final technical report for the project, "Development of Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)." This project was originally entitled, "Development of a PE GULFCAST Scheme and the Impact of Real Time IES Data on GULFCASTS" and was retitled, "Development of a Regional Coastal and Open Ocean Forecast System." The research tasks for this project have been to: develop, calibrate and validate the primitive equation based dynamical model component of the system; develop and implement the software for a modular, integrated forecast system; identify and acquire models from the scientific community to be utilized as modules within the forecast system; distribute and support the use of HOPS outside of Harvard; and demonstrate and validate HOPS via real time exercises on sea and land.

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Final Technical Report

Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)

ONR Contract N00014-90-J-1612

1 January 1990 - 31 December 1996

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This is the final technical report for the project "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)". This project was originally entitled "Development of a PE GULFCAST Scheme and the Impact of Real Time IES Data on GULFCASTS" and was retitled "Development of a Regional Coastal and Open Ocean Forecast System". The initial focus of the project was the development of a forecast scheme based on primitive equation dynamics for the Gulf Stream region. During the reporting period, the focus evolved away from a single identified region and a specific dynamical model towards a portable forecasting system, with the potential to include differing dynamical models, for use in any coastal, shelf or deep ocean region. The lead scientists at Harvard have been Dr. Hernan Arango and Dr. Patrick J. Haley, Jr. with significant additional support from Dr. Carlos J. Lozano and Wayne G. Leslie.

The research tasks for this project have been to: develop, calibrate and validate the primitive equation based dynamical model component of the system; develop and implement the software for a modular, integrated forecast system; identify and acquire models from the scientific community to be utilized as modules within the forecast system;

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distribute and support the use of HOPS outside of Harvard; and, demonstrate and validate HOPS via real time exercises on sea and land.

General software improvements to the HOPS system include: the addition of a primitive equation dynamical model to the dynamical model option; improvement in the ability to track software bug fixes and improvements (SCCS); utilization of a standard input/output data format (netCDF) to increase product portability; and, implementation of a procedure (GNUmake) to ease software installation.

Specific improvements to the primitive equation dynamical model are in the areas of: ability to work with high/steep bottom topography (2σ, ∇p); momentum flux computation for terrain-following coordinates; vertical sub-grid scale parameterization (Pacanowski and Philander, surface layer). The system is capable of being utilized in coastal regions now as coastal masking has been implemented. Spherical coordinates can be used, as well as "rotated spherical" coordinates. Nested physical domains of varying horizontal resolution can share information through n-level, 2-way nesting. New capabilities include: additional radiation boundary conditions (Orlanski, Modified Orlanski); OI data assimilation; lagrangian drifter simulators; surface flux forcing; and, coupled biological models.

The Harvard Ocean Prediction System (HOPS) is now a flexible, portable and generic system for nowcasting, forecasting and simulations. Recent reviews by Robinson [1996], Robinson *et al.* [1996b] and Lozano *et al.* [1996] provide a comprehensive presentation of the system and overview of its applications, including coupled physical-acoustical [Robinson and Lee, 1994] and physical-biological [McGillicuddy *et al.*, 1995 a,b] studies. A rigorous quantitative verification has been achieved for the Iceland-Faeroe Islands frontal system [Miller *et al.*, 1995 a,b; Robinson *et al.*, 1996a]. An additional significant calibration and verification study of the models, methodology and procedures is presented in Gangopadhyay *et al.*, (1997); Robinson and Gangopadhyay, (1997); Gangopadhyay and Robinson, (1997). Important aspects of HOPS have been developed as 6.1 research and subsequently transitioned to this 6.2 project.

The overall system schematic is shown on Fig. 1. The heart of the system for most coastal applications is a primitive equation physical dynamical model which has been spe-

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cially structured for accurate and efficient calculations over steep topography [Lozano, *et al.*, 1994; Haley, 1996]. Vertical coordinate options include sigma, hybrid and multiple sigma coordinate transformations which are calibrated for specific applications via sensitivity analyses to both vertical and horizontal resolutions [Sloan, 1996, Chapter II]. Horizontal coordinate options include multiple two-way nests [Sloan, *ibid.*]. A variety of physical, biological and acoustical, in situ and remotely sensed, data types have been assimilated in a variety of applications. The data analysis and management modules of HOPS represent a major resource of the Harvard system. HOPS methodology involves the construction of a best possible initial synoptic realization as a starting point for the assimilation of new synoptic data. There is an emphasis on the treatment of data prior to assimilation in order to maximize the impact of new data in the light of prior data. *Structured data models* [Lozano *et al.*, 1996] are utilized for this purpose, e.g., feature models or typical synoptic structures [Gangopadhyay *et al.*, 1997; Robinson and Gangopadhyay, 1997; Gangopadhyay and Robinson, 1997] and empirical orthogonal functions (EOFs) in one to three dimensions. Recent developments include: i) the use of temperature and salinity based, rather than velocity based, feature models which are more suitable over steep topography; ii) the addition of a dynamically balanced vertical velocity to the feature models for initialization and assimilations which will couple physics and biology; and, iii) the optical dynamical component (Fig. 1). For the construction of best possible synoptic realizations multiple data streams, including structured data models and seasonally adjusted historical synoptic realizations, are melded. The modularity of HOPS facilitates the selection of a subset of modules to form an efficient configuration for specific applications and also facilitates the addition of new or substitute modules.

A robust (suboptimal) optimal interpolation (OI) data assimilation scheme with weights set by simple engineering-type assumptions has been used in HOPS for several years [Lozano *et al.*, 1996]. OI was adopted in order to focus research resources on the assimilation of real ocean data sets rapidly into the ocean dynamical models for a first round of impact studies. A second quasioptimal assimilation scheme option, Error Subspace Statistical Estimation (ESSE), has been developed as part of a Ph.D. thesis, supported under 6.1, and recently added to the system under the continuing 6.2 project. A rational ap-

proach was used to identify an efficient statistical estimation scheme feasible for use in real time with real oceanic data sets. The ESSE goal is to determine the nonlinear evolution of the oceanic state by minimizing the most energetic errors under the constraints of the dynamical and measurement models and both of their uncertainties [Lermusiaux, 1997]. Error propagation is estimated via an ensemble forecast using the full nonlinear model. The evolving error subspace is characterized by singular error vectors and values, i.e., time evolving three dimensional error EOFs. Melding weights for assimilation are determined using a minimum error variance criterion. Importantly, melding occurs in the error subspace and is thus much less costly than a classical analysis with the full error covariances. The error subspace is updated at the melding step by combining the forecast principal errors, i.e., errors arising from the dynamical model and the loss of predictability, with the error covariances of the measurements.

Real time and at sea forecasts have been carried out for more than a decade in twenty sites in the Atlantic and Pacific Oceans and the Mediterranean Sea (Fig. 2). Those experiments which took place during the time period covered by this report were conducted in: the Iceland-Faeroe Frontal Region (1992 and 1993), the eastern Mediterranean (POEM-BC 1995 LIW Experiment), the Strait of Sicily (1994, 1995 and 1996 [NATO exercise Rapid Response 97]), the Haro Straits (1996) and the Tyrrhenian Sea Skerki Bank region (1996). Informal reports describing these experiments have been prepared and are available.

HOPS has now been developed to the level of a true operational forecast system, allowing for rapid set-up, implementation, and execution in a new observational or operational location with Harvard researchers functioning as a operational research group. The HOPS system has also been utilized by researchers at the following locations (alphabetically): CNR, Bologna, Italy; IMB, Ancona, Italy; IMS-METU, Erdemli, Turkey; IOLR, Haifa, Israel; JPL/NASA, Pasadena; NCMR, Athens, Greece; NOVA University; NRL-Stennis; Naval Postgraduate School; ORI, Tokyo, Japan; Rutgers University; SACLANT Undersea Research Centre, La Spezia, Italy; Scripps Institution; Univ. of Massachusetts, Dartmouth; Univ. of Rhode Island; and, Woods Hole Oceanographic Institution.

Refereed Publications Supported By This Project

Glenn, S.M. and A.R. Robinson (1990). Nowcasting and Forecasting of Oceanic Dynamic and Acoustic Fields, in *Computational Acoustics II* (D. Lee, A. Cakmak and R. Vichnevetsky, eds.),117–128, Elsevier Scientific Publishers, Amsterdam.

Siegmann, W.L., M.J. Jacobson, D. Lee, G. Botseas, A.R. Robinson (1990). Interfacing Mesoscale Ocean Prediction and Parabolic Acoustic Propagation Models, in *Computational Acoustics II* (D. Lee, A. Cakmak and R. Vichnevetsky, eds.), 155–168, Elsevier Scientific Publishers, Amsterdam.

Robinson, A.R., S.M. Glenn, W.L. Siegmann, D. Lee and G. Botseas (1991). Environmental Sensitivity Studies with an Interfaced Ocean-Acoustics System, in *Ocean Variability and Acoustic Propagation* (J.R. Potter and A. Warn-Varnas, eds.), 545–560, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Porter, D.L., S.M. Glenn, E.B. Dobson and A.R. Robinson (1991). GEOSAT: A U.S. Navy Spaceborne Altimeter, *Oceanus,* **33**(4) 50–57.

Glenn, S.M., D.L. Porter and A.R. Robinson (1991). A Synthetic Geoid Validation of Geosat Mesoscale Dynamic Topography in the Gulf Stream Region, *Journal of Geophysical Research — Oceans,* **96**(64) 7145–7166.

Mellberg, L.E., A.R. Robinson and G. Botseas (1991). Azimuthal Variation of Low Frequency Acoustic Propagation Through Asymmetric Gulf Stream Eddies, *Journal of Acoustical Society of America,* **89**(5), 2157–2167.

Robinson, A.R. (1992). Shipboard Prediction with a Regional Forecast Model, *The Oceanography Society Magazine,* **5**(1), 42–48.

Computational Acoustics. Volume 1: Scattering Supercomputing and Propagation (R.L. Lau, D. Lee and A.R. Robinson, editors), North-Holland, Amsterdam, The Netherlands. 456pp. 1993.

Computational Acoustics. Volume 2: Acoustic Propagation (D. Lee, A.R. Robinson and R. Vichnevetsky, editors), North-Holland, Amsterdam, The Netherlands. 457pp. 1993.

Surface Duct and Range Dependence Effects on Acoustic Propagation in the North Atlantic Drift Region, in *Computational Acoustics: Scattering, Supercomputing and Propagation: Volume 1* (R.L. Lau, D. Lee and A.R. Robinson, editors), North Holland, Amsterdam, The Netherlands, 19–38. 1993.

Environmental Input Sensitivities of an Interfaced Ocean-Acoustic System, in *Computational Acoustics: Scattering, Supercomputing and Propogation: Volume 1* (R.L. Lau, D. Lee and A.R. Robinson, editors), North Holland, Amsterdam, The Netherlands, 429–450. 1993.

Oceanography and Acoustics: Prediction and Propagation Models, Edited and with an Introduction by A.R. Robinson and D. Lee. American Inst. of Physics, New York. 257pp. 1994.

Robinson, A.R., J.C. Carman and S.M. Glenn (1994). A Dynamical System for Acoustic Applications, in *Oceanography and Acoustics: Prediction and Propagation Models*, (A.R. Robinson and D. Lee, editors),
American Inst. of Physics, New York, 80-117.

Siegmann, W.L., D. Lee, G. Botseas and A.R. Robinson (1994). Sensitivity Issues for Interfacing Mesoscale Ocean Prediction and Parabolic Acoustic Propagation Models, in *Oceanography and Acoustics: Prediction and Propagation Models* (A.R. Robinson and D. Lee, editors), American Inst. of Physics, New York, 133–160.

Willems, R.C., S.M. Glenn, M.F. Crowley, P. Malanotte-Rizzoli, R.E. Young, T. Ezer, G.L. Mellor, H.G. Arango, A.R. Robinson and C.-C. Lai (1994). Experiment Evaluates Ocean Models and Data Assimilation in the Gulf Stream (DAMEÉ-GSR), *EOS*, 75(34): 385, 391, 394.

Robinson, A.R. and D. Lee (1994). Ocean Variability, Acoustic Propagation and Coupled Models, *Oceanography and Acoustics: Prediction and Propagation Models* (A.R. Robinson and D. Lee, editors), American Inst. of Physics, New York, 1–6, 1994

Glenn, S.M. and A.R. Robinson (1995). Verification of an Operational Gulf Stream Forecasting Model, in *Quantitative Skill Assessment for Coastal Ocean Models,*

6

Coastal and Estuarial Studies, American Geophysical Union, **47**, 469–499.

Miller, A.J., P.-M. Poulain, A.R. Robinson, H.G. Arango, W.G. Leslie and A. Warn-Varnas (1995a). Quantitative Skill of Quasigeostrophic Forecasts of a Baroclinically Unstable Iceland Faeroe Front, *Journal of Geophysical Research*, **100**(C6), 10833–10849.

Miller, A.J., H.G. Arango, A.R. Robinson, W.G. Leslie, P.-M. Poulain, and A. Warn-Varnas (1995b). Quasigeostrophic Forecasting and Physical Processes of Iceland-Faeroes Frontal Variability, *Journal of Physical Oceanography* **25**, 1273–1295.

Robinson, A.R. (1996). Physical Processes, Field Estimation and Interdisciplinary Ocean Modeling, *Earth-Science Reviews*, 40(1/2), 3–54.

Robinson, A.R., H.G. Arango, A.J. Miller, A. Warn-Varnas, P.-M. Poulain, and W.G. Leslie (1996a). Real-Time Operational Forecasting on Shipboard of the Iceland-Faeroe Frontal Variability, *Bulletin of the American Meteorological Society*, 77(2), 243–259.

Robinson, A.R., H.G. Arango, A. Warn-Varnas, W.G. Leslie, A.J. Miller, P.J. Haley and C.J. Lozano (1996b). Real-Time Regional Forecasting, *Modern Approaches to Data Assimilation in Ocean Modeling* (P. Malanotte-Rizzoli, editor), Elsevier Oceanography Series, 377–410, Elsevier Science, The Netherlands.

Lozano, C.J., A.R. Robinson, H.G. Arango, A. Gangopadhyay, N.Q. Sloan, P.J. Haley, L.A. Anderson and W.G. Leslie (1996). An Interdisciplinary Ocean Prediction System: Assimilation Strategies and Structured Data Models, *Modern Approaches to Data Assimilation in Ocean Modeling* (P. Malanotte-Rizzoli, editor), Elsevier Oceanography Series, 413–452, Elsevier Science, The Netherlands.

Robinson, A.R. (1997). Forecasting and Simulating Coastal Ocean Processes and Variabilities With The Harvard Ocean Prediction System, in *Coastal Ocean Prediction* (C.N.K. Mooers, editor), Coastal and Estuarine Studies Monograph Series, American Geophysical Union, in press.

Sellschopp, J. and A.R. Robinson (1997). Definition and Forecasting of Ocean Conditions During Rapid Response, *Proc. Int. Conf. "Rapid Environmental Assessment"*, Lerici, Italy, Mar. 10-14, 1997.

Gangopadhyay, A., A.R. Robinson, and H.G. Arango (1997). Circulation and Dynamics of the Western North Atlantic, I: Multi-Scale Feature Models, *Journal of Atmospheric and Oceanic Technology*, in press.

Robinson, A.R. and A. Gangopadhyay (1997). Circulation and Dynamics of the Western North Atlantic, II: Dynamics of Meanders and Rings, *Journal of Atmospheric and Oceanic Technology.* In press.

Gangopadhyay, A. and A.R. Robinson (1997). Circulation and Dynamics of the Western North Atlantic, III: Forecasting the Meanders and Rings, *Journal of Atmospheric and Oceanic Technology*, in press.

Robinson, A.R., J. Sellschopp, A. Warn-Varnas, W.G. Leslie, P.J. Haley, Jr., P.F.J. Lermusiaux and L.A. Anderson (1997). The Atlantic Ionian Stream, *Journal of Marine Systems*, in press.

Harvard Reports Supported By This Project

Lozano, C.J., P.J. Haley, Jr., H.G. Arango, N.Q. Sloan and A.R. Robinson (1994). Harvard coastal/deep water primitive equation model, *Harvard Open Ocean Model Reports*, **52**, 15pp.

Haley, P.J., Jr. (1996). GRIDS, *Harvard Open Ocean Model Reports*, **54**, 13pp.

Robinson, A.R., C.J. Lozano, W.G. Leslie, L.A. Anderson, P.J. Haley, Jr. and J.A. Dusenberry (1997). Scientific objectives and plans for real-time simulation experiment and operations: Plankton Patchiness Studies by Ship and Satellite, *Harvard Open Ocean Model Reports*, **56**, 37pp.

Informal reports describing operational exercises are also available.

6.1 Research Transitioned to 6.2

McGillicuddy, D.J., J.J. McCarthy and A.R. Robinson (1995a). Coupled Physical and Biological Modeling of the Spring Bloom in the North Atlantic, I: Model Formulation and One Dimensional Bloom Processes, *Deep-Sea Research*, I, 42(8), 1313–1357.

McGillicuddy, D.J., A.R. Robinson and J.J. McCarthy (1995b). Coupled Physical and Biological Modeling of the Spring Bloom in the North Atlantic, II: Three Dimensional Bloom and Post-Bloom Effects, *Deep-Sea Research*, I, 42(8), 1359-1398.

Sloan, N.Q., III (1996). Dynamics of a Shelf-Slope Front: Process Studies and Data-Driven Simulations in the Middle Atlantic Bight, Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

Lermusiaux, P.F.J. (1997). Error Subspace Data Assimilation Methods for Ocean Field Estimation: Theory, Validation, Applications, Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

A – POLYMODE
B – Nares Abyssal Plain (*)
C – NOAMP Site
D – California Current (*)
E – Gulfcast/NOGULFS (*)
F – Iceland Faeroes Front (*)
G – Eastern Mediterranean (*)
H – Northeast Pacific (*)
I – Bermuda (*)
J – AthenA (*)
K – JGOFS (*)
L – Strait of Sicily (*)
M – Haro Straits (*)
N – Black Sea
O – Adriatic
P – Shelf/Slope PRIMER (*)
Q – Drake's Passage
R – North Sea
S – Plankton Patchiness (*)
T – Skerki Bank (*)
(*) = Realtime / at Sea